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WOULD A LIGHT HIGGS DETECTION IMPLY NEW PHYSICS? *

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Abstract

Depending on the Higgs-boson and top-quark masses, M_H and M_t , the effective potential of the Standard Model can develop a non-standard minimum for values of the field much larger than the weak scale. In those cases the standard minimum becomes metastable and the possibility of decay to the non-standard one arises. Comparison of the decay rate to the non-standard minimum at finite (and zero) temperature with the corresponding expansion rate of the Universe allows to identify the region, in the (M_H, M_t) plane, where the Higgs field is sitting at the standard electroweak minimum. Since that region depends on the cutoff scale Λ , up to which we believe the Standard Model, the discovery of the Higgs boson, mainly at LEP-200, might put an upper bound (below the Planck scale) on the scale of new physics Λ .

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1 Introduction

For particular values of the Higgs boson and top quark masses, M_H and M_t , the effective potential of the Standard Model (SM) develops a deep non-standard minimum for values of the field $\phi \gg G_F^{-1/2}$ [1]. In that case the standard electroweak (EW) minimum becomes metastable and might decay into the non-standard one. This means that the SM might not accomodate certain regions of the plane (M_H, M_t) , a fact which can be intrinsically interesting as evidence for new physics. Of course, the mere existence of the non-standard minimum, and also the decay rate of the standard one into it, depends on the scale Λ up to which we believe the SM results. In fact, one can identify Λ with the scale of new physics.

In this talk I will review the present situation on the above issue and its relevance for evidence of new physics if a light Higgs is detected experimentally, most likely at LEP-200.

2 When the EW minimum becomes metastable?

The preliminary question one should ask is: When the standard EW minimum becomes metastable, due to the appearance of a deep non-standard minimum? This question was addressed in past years [1] taking into account leading log and part of next-to-leading log corrections. More recently, calculations have incorporated all next-to-leading log corrections [2, 3]. In particular in ref. [3] next-to-leading log corrections are resummed to all-loop by the renormalization group equations (RGE), and pole masses for the top-quark and the Higgs-boson are considered. From the requirement of a stable (not metastable) standard EW minimum we obtain a lower bound on the Higgs mass, as a function of the top mass, labelled by the values of the SM cutoff (stability bounds). Our result [3] is lower than previous estimates by $\mathcal{O}(10)$ GeV.

The one-loop effective potential of the SM improved by two-loop RGE has been shown to be highly scale independent [4] and, therefore, very reliable for the present study. It has stationary points at

$$\phi^2 = \frac{2m^2}{\tilde{\lambda}}; \quad \tilde{\lambda} = \lambda - \frac{3}{8\pi^2} h_t^4 \left(\log \frac{h_t^2}{2} - 1 \right) \quad (1)$$

where m^2 and λ are the tree-level mass and quartic coupling parameters of the SM, and h_t is the top-quark Yukawa coupling. All parameters in (1) are running with the renormalization scale, that has been identified with the field ϕ , and we are keeping, to simplify the presentation, only the top-quark Yukawa coupling in the one-loop correction.

The second derivative of the effective potential at (1) is

$$V''(\phi) = 2m^2 + \frac{1}{2}\beta_\lambda \phi^2 \quad (2)$$

A quick glance at (1) shows that eq. (1) can be satisfied for values of the field $\phi \gg v = 246.22$ GeV, provided that, for those values of the field, $\tilde{\lambda} \sim 0$. In this case, since $m^2 \sim 10^2$ GeV for all values of the scale, the first term in (2) is negligible and the second term will control the nature of the stationary point. In particular,

$$\begin{aligned} \beta_\lambda < 0 &\implies V'' < 0 \text{ (MAXIMUM)} \\ \beta_\lambda > 0 &\implies V'' > 0 \text{ (MINIMUM)} \end{aligned}$$

In Fig. 1 we show (thick solid line) the shape of the effective potential for $M_t = 175$ GeV and $M_H = 121.7$ GeV. We see the appearance of the non-standard maximum, ϕ_M , while the

global non-standard minimum has been cutoff at M_P . We can see from Fig. 1 the steep descent from the non-standard maximum. Hence, even if the non-standard minimum is beyond the SM cutoff, the standard minimum becomes metastable and can be destabilized. So for fixed values of M_H and M_t the condition for the standard minimum not to become metastable is

$$\phi_M \gtrsim \Lambda \quad (3)$$

Condition (3) makes the stability condition Λ -dependent. In fact we have plotted in Fig. 2 the stability condition on M_H versus M_t for two different values of Λ , 10^{19} GeV (left panel) and 10 TeV (right panel). In both figures the stability region corresponds to the region above the dashed curves.

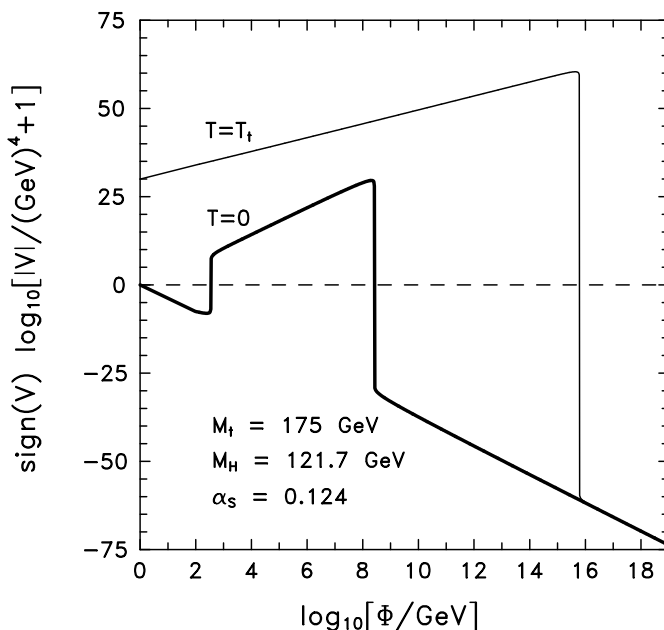


Figure 1: Plot of the effective potential for $M_t = 175$ GeV, $M_H = 121.7$ GeV at $T = 0$ (thick solid line) and $T = T_t = 2.5 \times 10^{15}$ GeV (thin solid line).

3 When the EW minimum decays?

In the last section we have seen that in the region of Fig. 2 below the dashed lines the standard EW minimum is metastable. However we should not draw physical consequences from this fact since we still do not know at which minimum does the Higgs field sit. Thus, the real physical constraint we have to impose is avoiding the Higgs field sitting at its non-standard minimum. In fact the Higgs field can be sitting at its non-standard minimum at zero temperature because:

1. The Higgs field was driven from the origin to the non-standard minimum at finite temperature by thermal fluctuations in a non-standard EW phase transition at high temperature. This minimum evolves naturally to the non-standard minimum at zero temperature. In this case the standard EW phase transition, at $T \sim 10^2$ GeV, will not take place.
2. The Higgs field was driven from the origin to the standard minimum at $T \sim 10^2$ GeV, but decays, at zero temperature, to the non-standard minimum by a quantum fluctuation.

In Fig. 1 we have depicted the effective potential at $T = 2.5 \times 10^{15}$ GeV (thin solid line) which is the corresponding transition temperature. Our finite temperature potential [5] incorporates plasma effects [6] by one-loop resummation of Debye masses [7]. The tunnelling probability per unit time per unit volume was computed long ago for thermal [8] and quantum [9] fluctuations. At finite temperature it is given by $\Gamma/\nu \sim T^4 \exp(-S_3/T)$, where S_3 is the euclidean action evaluated at the bounce solution $\phi_B(0)$. The semiclassical picture is that unstable bubbles are nucleated behind the barrier at $\phi_B(0)$ with a probability given by Γ/ν . Whether or not they fill the Universe depends on the relation between the probability rate and the expansion rate of the Universe. By normalizing the former with respect to the latter we obtain a normalized probability P , and the condition for decay corresponds to $P \sim 1$. Of course our results are trustable, and the decay actually happens, only if $\phi_B(0) < \Lambda$, so that the similar condition to (3) is

$$\Lambda < \phi_B(0) \quad (4)$$

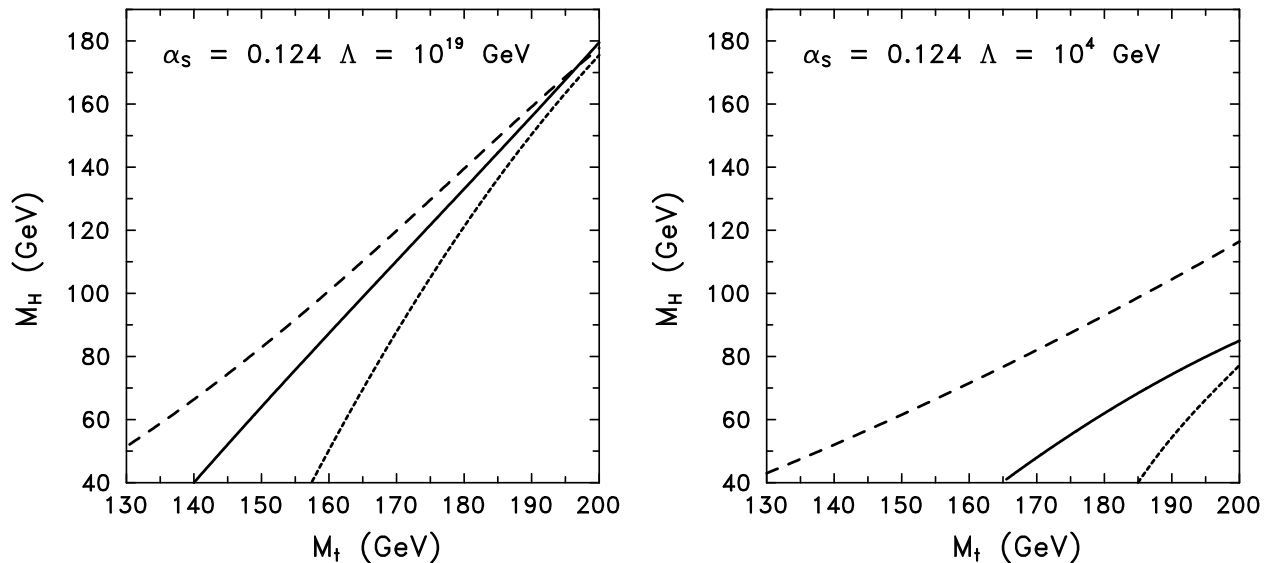


Figure 2: Lower bounds on M_H as a function of M_t , for $\Lambda = 10^{19}$ GeV (left panel) and 10 TeV (right panel). The dashed curves correspond to the stability bounds of Section 2 and the solid (dotted) ones to the metastability bounds of Section 3 at finite (zero) temperature.

The condition of no-decay (metastability condition) has been plotted in Fig. 2 (solid lines) for the two values of Λ , 10^{19} GeV (left panel) and 10 TeV (right panel). In both cases the region between the dashed and the solid line corresponds to a situation where the non-standard minimum exists but there is no decay to it at finite temperature. In the region below the solid lines the Higgs field is sitting already at the non-standard minimum at $T \sim 10^2$ GeV, and the standard EW phase transition does not happen.

We also have evaluated the tunnelling probability at zero temperature from the standard EW minimum to the non-standard one. The result of the calculation should translate, as in the previous case, in lower bounds on the Higgs mass for different values of Λ . The corresponding

bounds are shown in Fig. 2 in dotted lines. Since the dotted line lies always below the solid one, the possibility of quantum tunnelling at zero temperature does not impose any extra constraint.

As a consequence of all improvements in the calculation, our bounds are lower than previous estimates [10]. To fix ideas, for $M_t = 175$ GeV, the bound reduces by ~ 10 GeV for $\Lambda = 10^4$ GeV, and ~ 30 GeV for $\Lambda = 10^{19}$ GeV.

4 Does a light Higgs imply new physics?

From the previous discussion it should be clear by now that the Higgs and top mass measurements could serve to discriminate between the SM and its extensions, and to provide information about the scale of new physics Λ . In Fig. 3 (left panel) we give the SM lower bounds on M_H for $\Lambda \gtrsim 10^{15}$ (thick lines) and the upper bound on the mass of the lightest Higgs boson in the minimal supersymmetric standard model (MSSM) (thin lines) for $\Lambda_{\text{SUSY}} \sim 1$ TeV. Taking, for instance, $M_t = 180$ GeV, which coincides with the central value recently reported by CDF+D0 [11], and $M_H \gtrsim 130$ GeV, the SM is allowed and the MSSM is excluded. On the other hand, if $M_H \lesssim 130$ GeV, then the MSSM is allowed while the SM is excluded. Likewise there are regions where the SM is excluded, others where the MSSM is excluded and others where both are permitted or both are excluded.

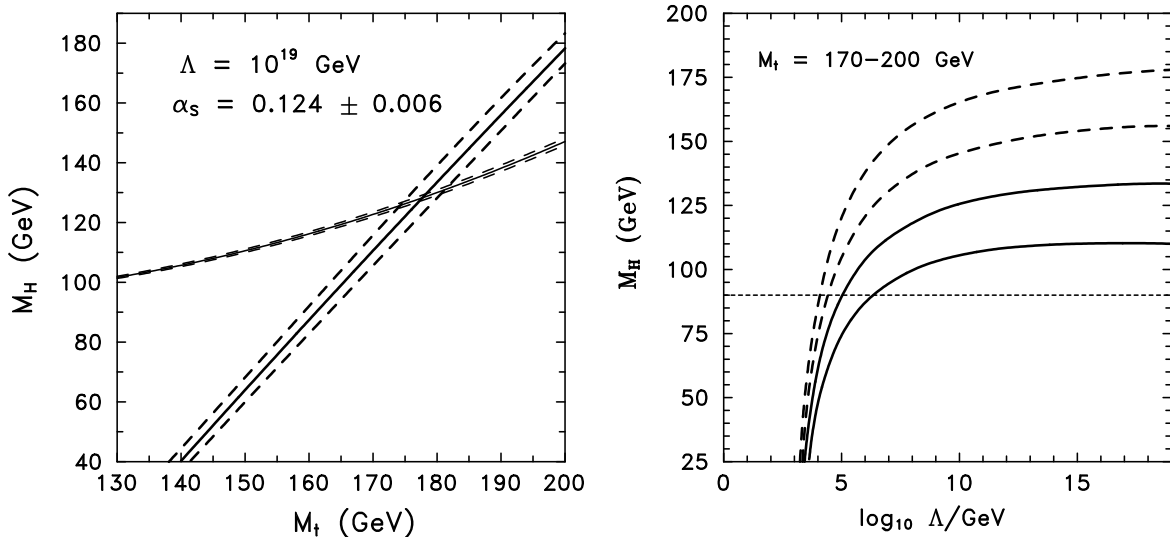


Figure 3: Left panel: SM lower bounds on M_H (thick lines) as a function of M_t , for $\Lambda = 10^{19}$ GeV, from metastability requirements, and upper bounds on the lightest Higgs boson mass in the MSSM (thin lines) for $\Lambda_{\text{SUSY}} = 1$ TeV. Right panel: SM lower bounds on M_H from metastability requirements as a function of Λ for different values of M_t .

Finally from the bounds $M_H(\Lambda)$ (see Fig. 3, right panel) one can easily deduce that a measurement of M_H might provide an **upper bound** (below the Planck scale) on the scale of new physics provided that

$$M_t > \frac{M_H}{2.25 \text{ GeV}} + 123 \text{ GeV} \quad (5)$$

Thus, the present experimental bound from LEP, $M_H > 64$ GeV, would imply, from (5), $M_t > 152$ GeV, which is fulfilled by experimental detection of the top [11]. Even non-observation of the Higgs at LEP-200 (i.e. $M_H \gtrsim 95$ GeV), would leave an open window ($M_t \gtrsim 163$ GeV) to the possibility that a future Higgs detection at LHC could lead to an upper bound on Λ . Moreover, Higgs detection at LEP-200 would put an upper bound on the scale of new physics. Taking, for instance, $M_H \lesssim 95$ GeV and $170 \text{ GeV} < M_t < 180 \text{ GeV}$, then $\Lambda \lesssim 10^7$ GeV, while for $180 \text{ GeV} < M_t < 190 \text{ GeV}$, then $\Lambda \lesssim 10^4$ GeV, as can be deduced from the right panel of Fig. 3.

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